
Getting the most
from Long BaseLine
experiments @ FNAL
Theoretical Overview

Neutrinos (ν's) have helped us for deeper understanding of the SM

They :

were the KEY to the weak interactions

were almost invisible carriers of energy

were the first state with only a chiral gauge charge

were introduced as massless particles :

No mixing nor CP violation in the lepton sector!

SK+SNO+KamLAND+K2K indicate that ν's change flavor (@ 95%CL):

$$|\Delta m^2| = 2.4\,(1^{+0.21}_{-0.26}) \times 10^{-3}\ \mathrm{eV}^2 \quad \delta m^2 = 7.92\,(1 \pm 0.09) \times 10^{-5}\ \mathrm{eV}^2$$

Both with large (one of them, maximal(?)) mixing angles:

$$\sin^2\theta_{23} = 0.44\,(1^{+0.41}_{-0.22}) \qquad \sin^2\theta_{12} = 0.314\,(1^{+0.18}_{-0.15})$$

$$sin^2\theta_{13} < 0.032$$

G.L. Fogli et al

It is possible to weigh neutrinos with cosmology, from WMAP+LSS:

$$\Sigma_i m_{\nu_i} \lesssim 1\ \mathrm{eV}$$

ν metamorphosis ☛ New Physics Beyond the Standard Model

+

New Energy scale associated to it

ν's could help us for a deeper understanding of the SM:

(?) Complex vacuum structure: Hierarchy problem

(?) Many a priori unknown parameters: Flavor puzzle!

Outline

The fundamental questions

Three neutrino mixing: CLONES!

Near term Long BaseLine experiments: T2K &NuMI
neutrinos & antineutrinos

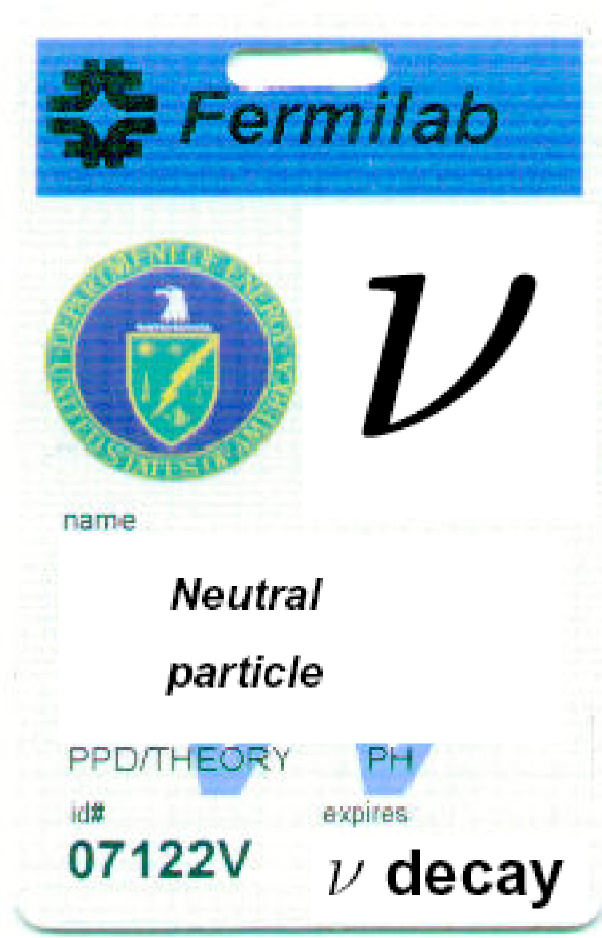
NuMI with neutrinos & antineutrinos

THE RACE FOR THE HIERARCHY!

SuperNOvA: NuMI with ONLY neutrinos

T2K and NOvA: ONLY neutrinos

What is the neutrino IDentity?



DIRAC

$$\nu \neq \bar{\nu}$$

$$Y^{\nu}\overline{L}\tilde{\phi}\nu_R \ + \text{h.c}$$

L is conserved

MAJORANA

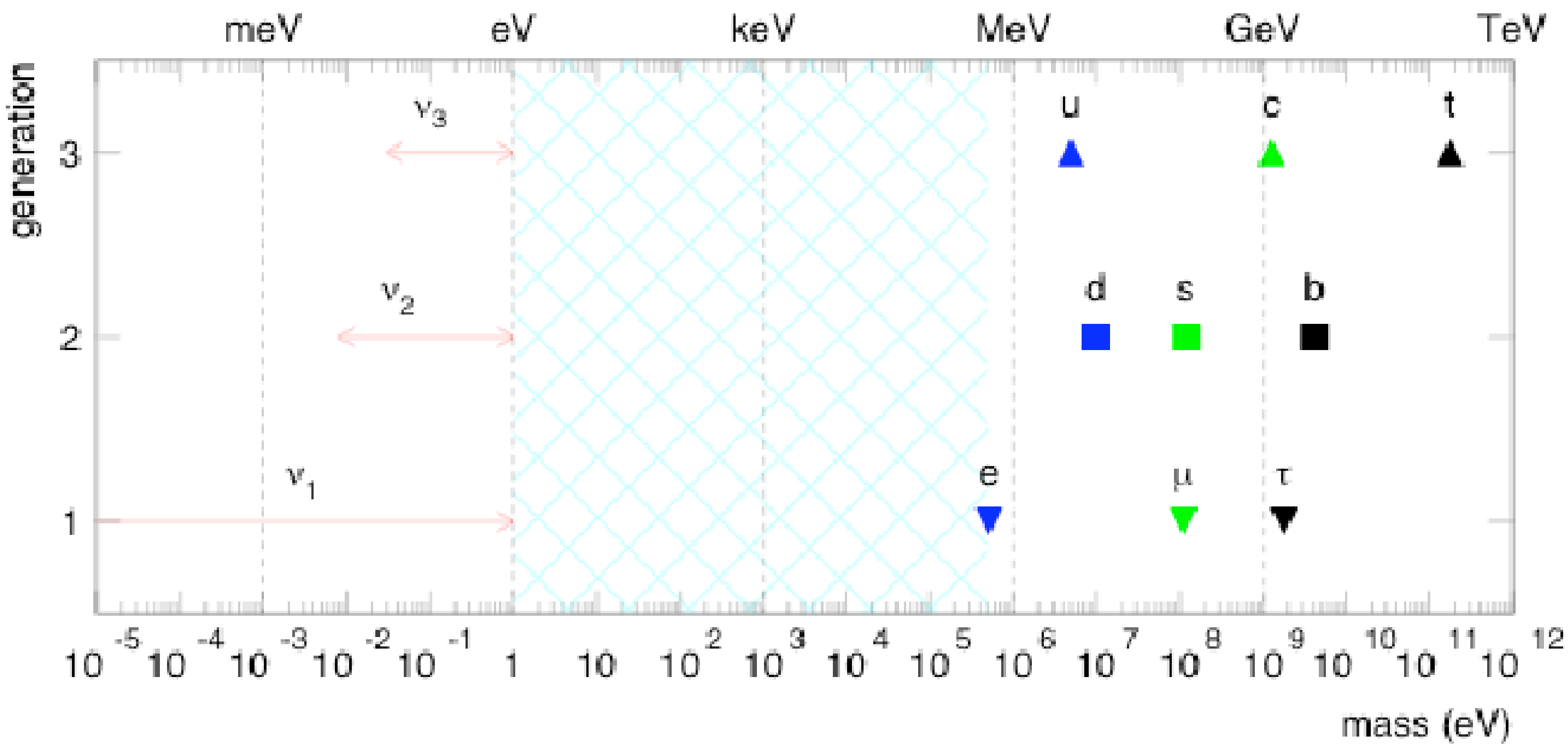
$$\nu = \bar{\nu}$$

$$\overline{\nu_R} M_R \, \nu_R{}^c$$

L is violated

What is the neutrino IDentity? Is there a L number conserved?

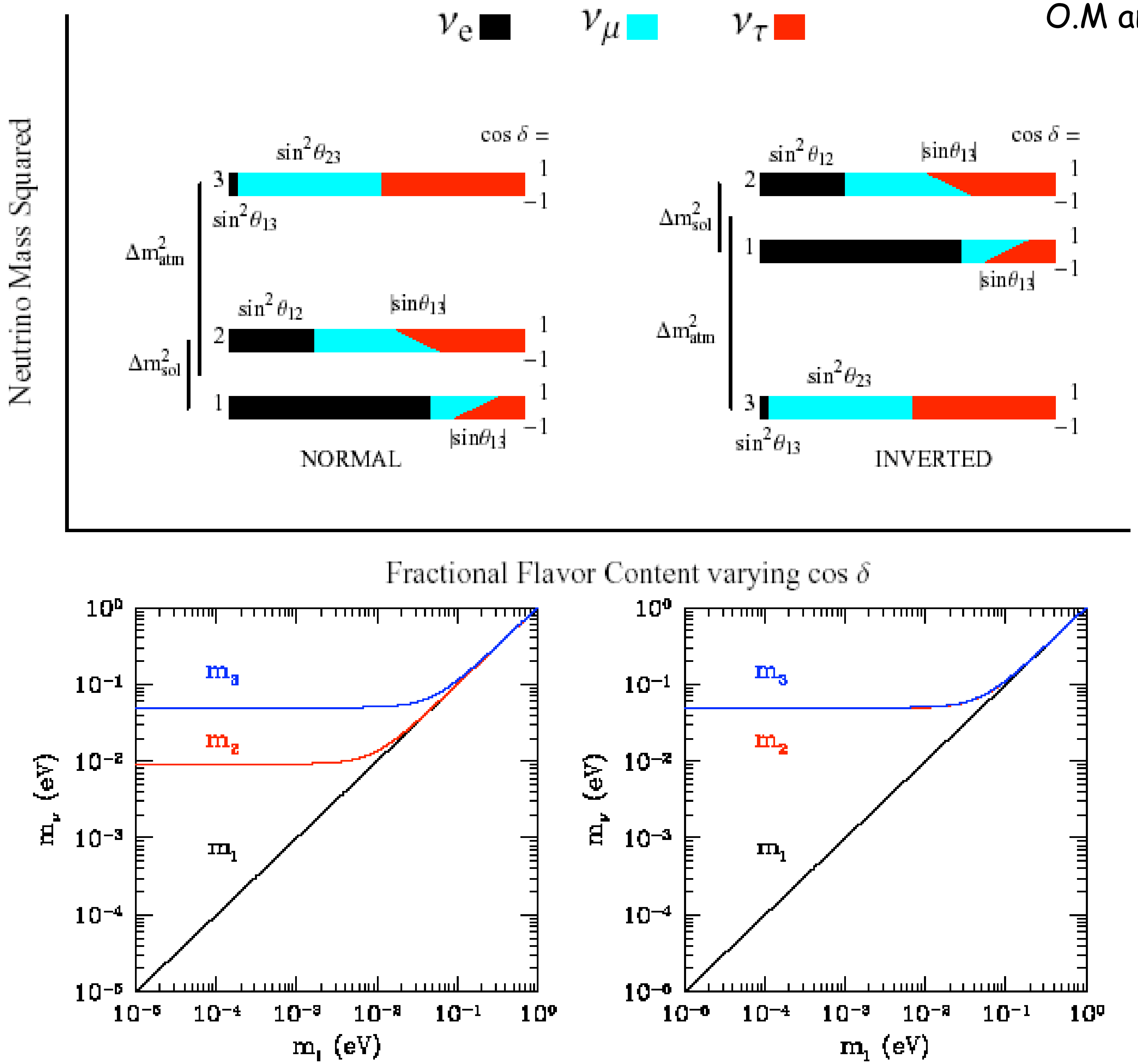
What is the absolute scale of neutrino masses?



What is the neutrino IDentity? Is there a L number conserved?

What is the absolute scale of neutrino masses?

O.M and S. Parke, PRD (2004)



What is the neutrino IDentity? Is there a L number conserved?

What is the absolute scale of neutrino masses?

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$ Neutrinoless double beta decay

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$ Tritium experiments

$$\Sigma = \Sigma m_\nu$$ Cosmology

A. Goobar et al, astro-ph/0602155

CMB+LSS+SNIa+BAO!

$$\sum m_\nu < 0.5 \text{ eV} \quad @95\%\text{CL}$$

What is the neutrino IDentity? Is there a L number conserved?

What is the absolute scale of neutrino masses?

Is there a new physics scale >>> EW scale behind?

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\mathcal{L}^{d=6} + \cdots$$

$$\frac{c_{\alpha\beta}}{2\Lambda}\,\overline{L_\alpha}\;\tilde{\phi}\;\tilde{\phi}^T\;(L_\beta)^c + \text{h.c}$$

S. Weinberg, PRL (1979)

$$(m_\nu)_{\alpha\beta} = \frac{c_{\alpha\beta}}{2}\frac{v^2}{\Lambda}$$

What is the neutrino IDentity? Is there a L number conserved?

What is the absolute scale of neutrino masses?

Is there a new physics scale >>> EW scale behind?

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\mathcal{L}^{d=6} + \cdots$$

$$\frac{c_{\alpha\beta}}{2\Lambda}\,\overline{L_\alpha}\,\tilde{\phi}\,\tilde{\phi}^T\,(L_\beta)^c + \mathrm{h.c}$$

S. Weinberg, PRL (1979)

O(1)

$$(m_\nu)_{\alpha\beta} = \frac{c_{\alpha\beta}}{2}\frac{v^2}{\Lambda}$$

$$M_R = \Lambda$$

See-saw mechanism: Small neutrino masses NATURALLY EXPLAINED!

What is the neutrino IDentity? Is there a L number conserved?

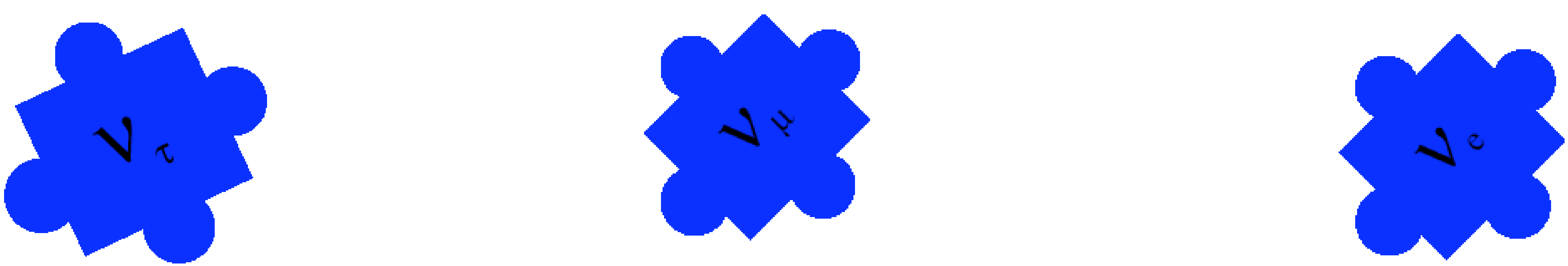
What is the absolute scale of neutrino masses?

Is there a new physics scale >>> EW scale behind?

Do neutrinos play a role in baryogenesis?

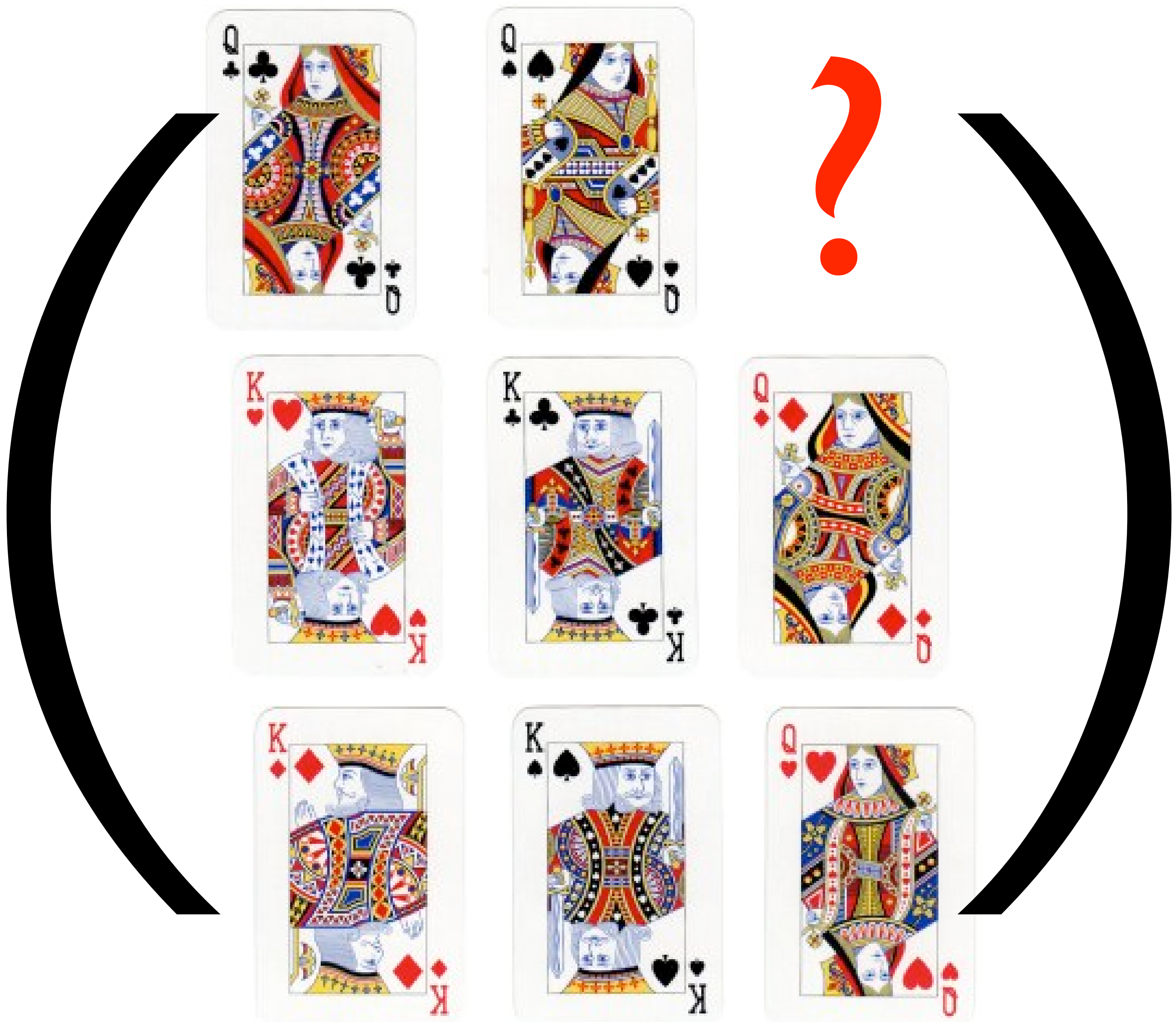
Is CP Violated in the Leptonic Sector?

These questions have opened up a new perspective of the FLAVOR PUZZLE. We WANT and We NEED to know the answers....



Our safest BET is to measure precisely the neutrino mass matrix...

$U_{MNSP} \sim$

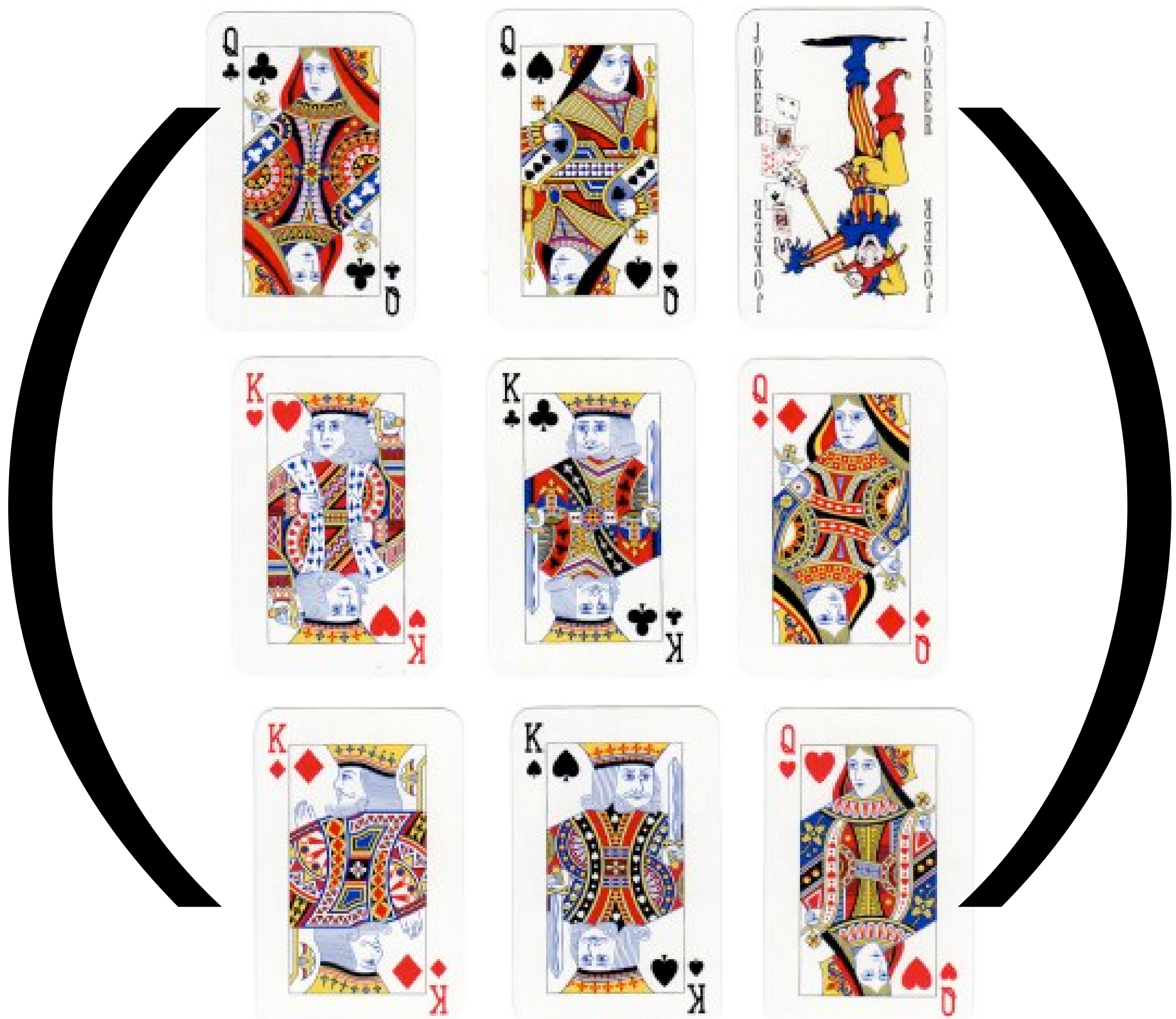


Our safest BET is to measure precisely the neutrino mass matrix...

$U_{MNSP} \sim$

Our safest BET is to measure precisely the neutrino mass matrix...

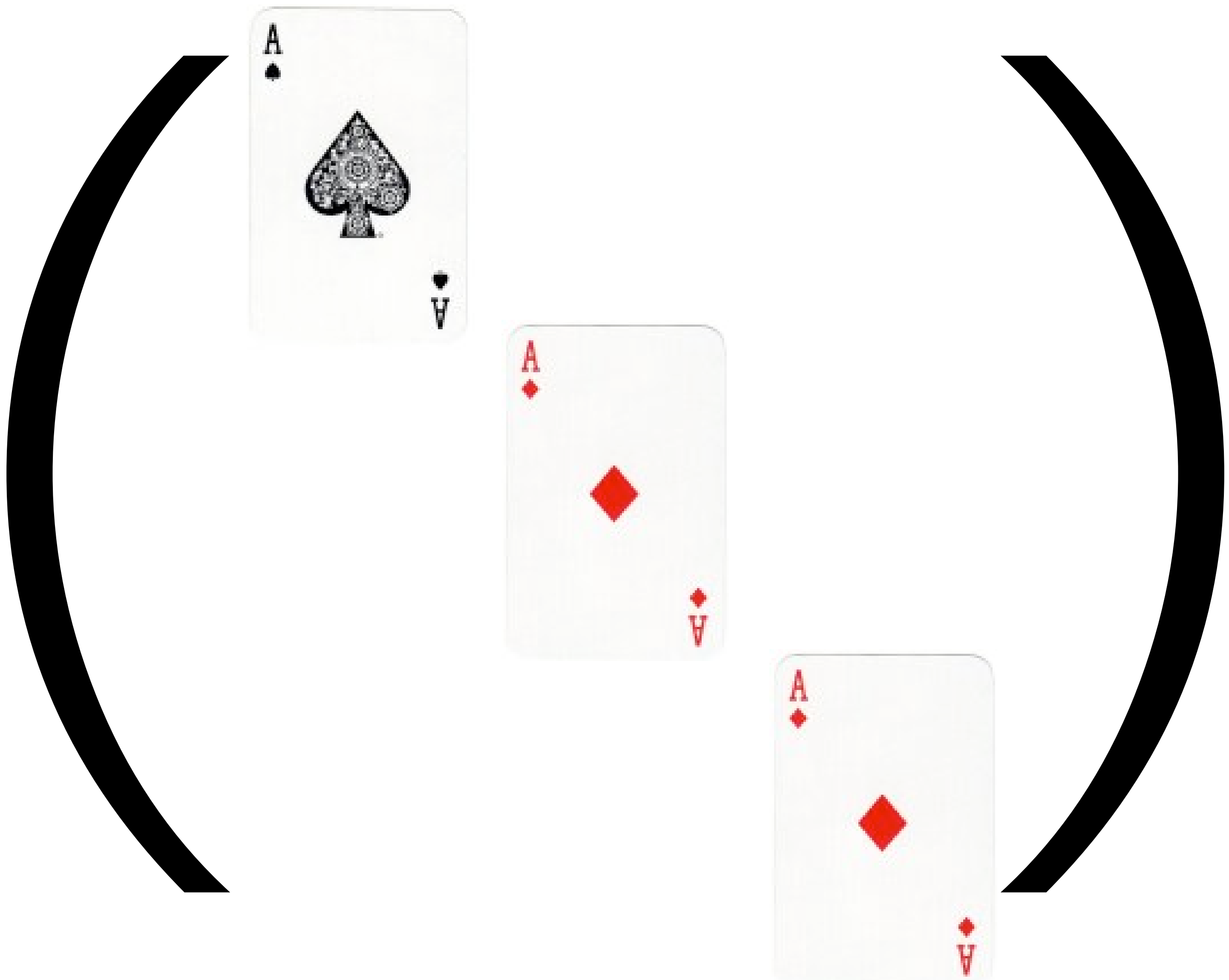
$$U_{MNSP} \sim$$



And test symmetries CP, CPT, maximal mixing?

Which is totally different from its quark counterpart...

$$|U_{CKM}| \sim$$



Clue about the origin of mixing and lepto-quark symmetries?

STANDARD THREE NEUTRINO MIXING

$$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\nu_\mu \leftrightarrow \nu_\tau$ $\nu_\mu \leftrightarrow \nu_e$ $\nu_e \longrightarrow \nu_{\mu,\tau}$

Atmospheric
L~1000 km/
E~GeV

Solar
L>>1000km
E<<GeV

$0\nu\beta\beta$
Majorana
phases

STANDARD THREE NEUTRINO EVOLUTION

$$i\frac{d}{dx}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{2E} U_{PMNS} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{12} & 0 \\ 0 & 0 & \Delta m^2_{13} \end{pmatrix} U^\dagger_{PMNS} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

THE OBSERVABLES

THE KNOWNS: θ_{23}, θ_{12}

$|m^2_{23}| >> m^2_{12}$

More precision is CRUCIAL:

a) measure unknowns

b) test symmetries

THE UNKNOWNS:

$sin^2\theta_{13} < 0.032$
@95%CL G.L. Fogli et al

θ_{13}

$\sin\delta$

HIERARCHY

$sign(\cos 2\theta_{23})$

Precision oscillation experiments

NEAR TERM

NEXT-to-

NEXT-to-NEXT

α_1, α_2 $0\nu\beta\beta$

m^2_1, m^2_3 Cosmology, Tritium, $0\nu\beta\beta$

In vacuum:

$$P_{\nu_\mu \nu_e (\bar{\nu}_\mu \bar{\nu}_e)} = s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E}$$ Atmospheric

$$+ c_{23}^2 \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$ Solar

$$+ \tilde{J} \cos\left(\pm\delta - \frac{\Delta m_{13}^2 L}{4E}\right) \frac{\Delta m_{12}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E}$$ Interference

$$J \equiv \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sim 2 \sin\theta_{13}$$

In matter:

$$\sin\Delta_{13} \rightarrow \frac{\Delta_{13}}{\Delta_{13} \mp aL} \sin(\Delta_{13} \mp aL)$$

$$\sin\Delta_{12} \rightarrow \frac{\Delta_{12}}{\Delta_{12} \mp aL} \sin(\Delta_{12} \mp aL)$$

MATTER INDUCES FAKE CP VIOLATION!

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E} \qquad a = G_F n_e / \sqrt{2}$$

The attack of the clones!

(θ'_{13}, δ') are solutions of

$$
\left.\begin{aligned}
P_{\nu_e\nu_\mu}(\theta'_{13}, \delta') &= P_{\nu_e\nu_\mu}(\theta_{13}, \delta) \\
P_{\bar\nu_e\bar\nu_\mu}(\theta'_{13}, \delta') &= P_{\bar\nu_e\bar\nu_\mu}(\theta_{13}, \delta)
\end{aligned}\right\} \text{ At fixed E and L}
$$

Appear when the full range of the parameters is considered and the energy dependence of the signal (after considering backs and effs) is NOT significant enough.

INTRINSIC $\rightarrow P(\theta'_{13}, \delta') = P(\theta_{13}, \delta)$

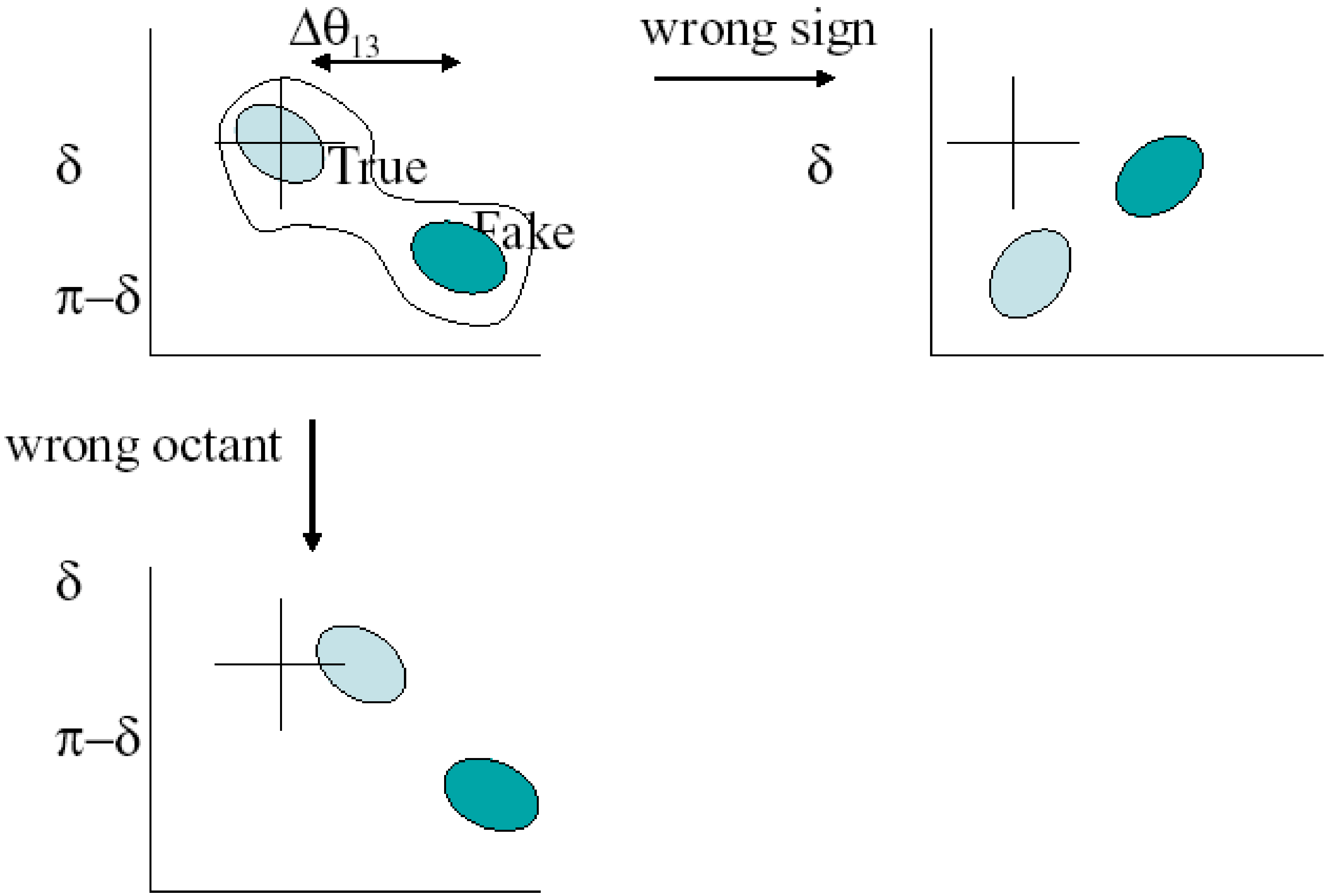
Burguet et al, NPB (2001).

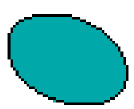
SIGN Δm^2_{13} $\rightarrow P(\theta'_{13}, \delta', -\Delta m^2_{13}) = P(\theta_{13}, \delta)$

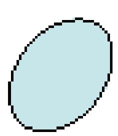
H. Minakata and H. Nunokawa, JHEP (2001);
V. Barger PRD (2002).

θ_{23} OCTANT $\rightarrow P(\theta'_{13}, \delta', \frac{\pi}{2} - \theta_{23}) = P(\theta_{13}, \delta)$

G. L. Fogli and E. Lisi PRD (1996);
V. Barger PRD (2002).



Position of  depends STRONGLY ON THE E, L

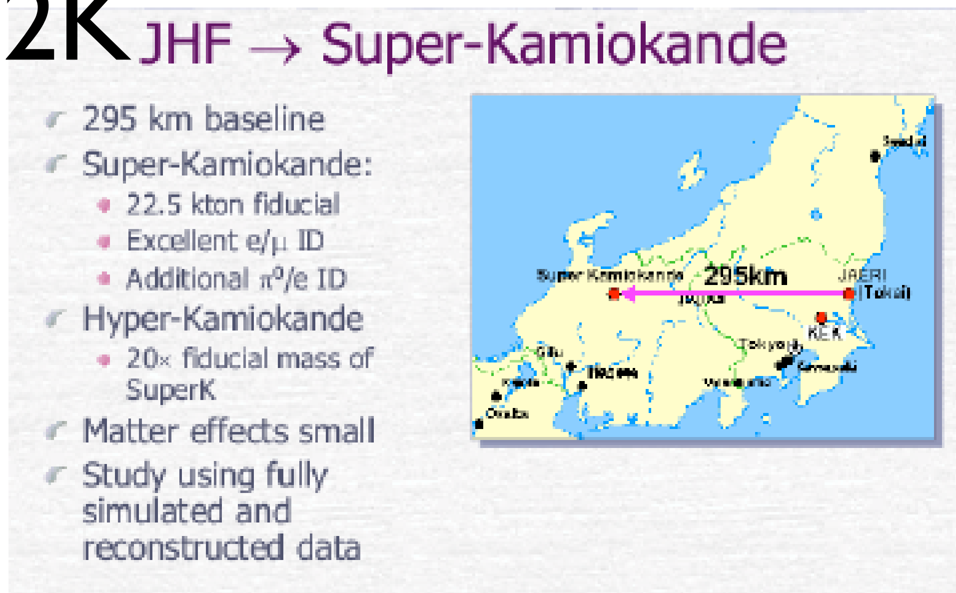
Position of  is E, L independent

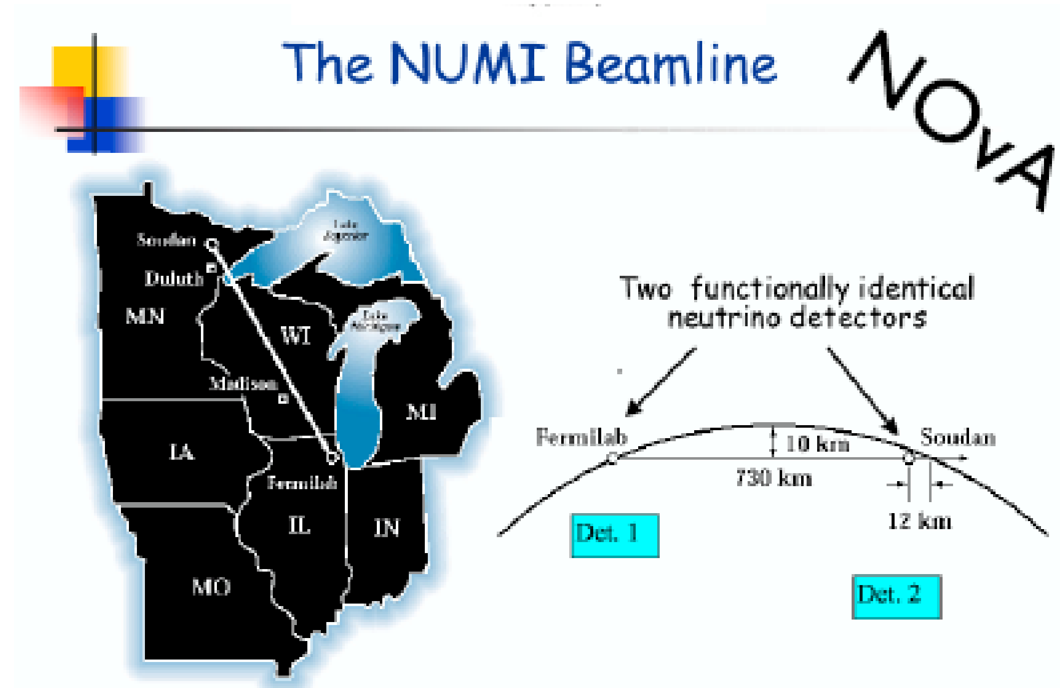
In vacuum all are CP conserving or all CP violating $\delta' = \pi - \delta$

A lot of work devoted to resolve the degeneracies, I will focus mostly on FNAL and T2K neutrino beams

SPECTRAL INFORMATION->BNL WB P.HUBER'S TALK

T2K



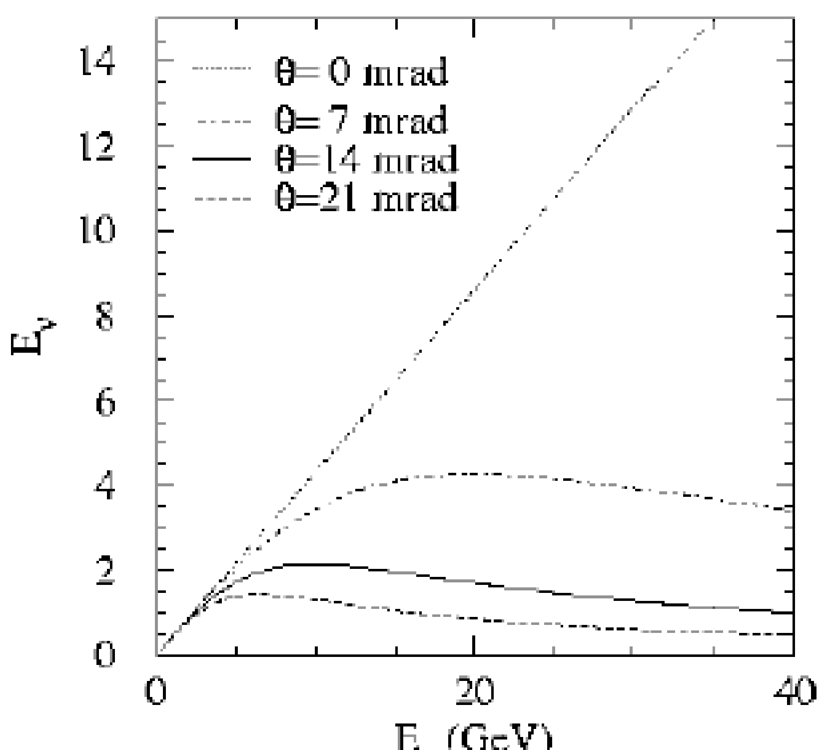


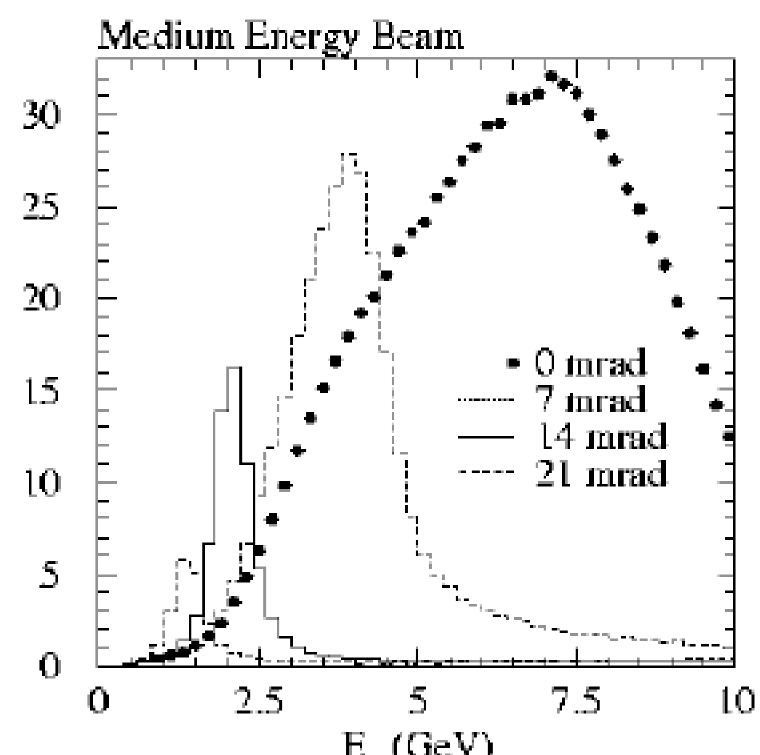
By using a conventional, albeit more intense, neutrino beam:

$$\pi^+ \rightarrow \mu^+ \nu_\mu \qquad < 1\% \nu_e$$

In an Off-Axis detector location

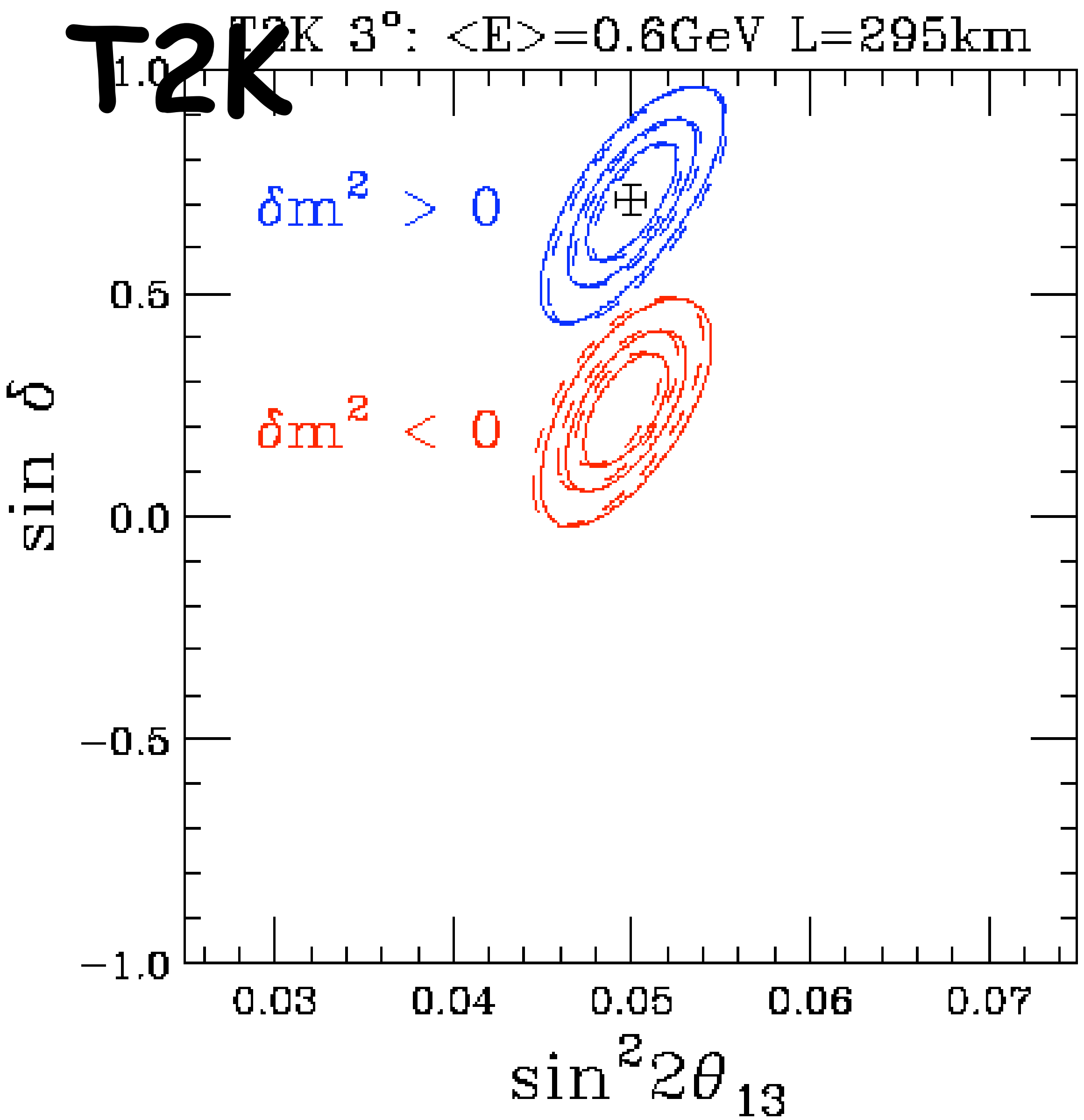
$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$



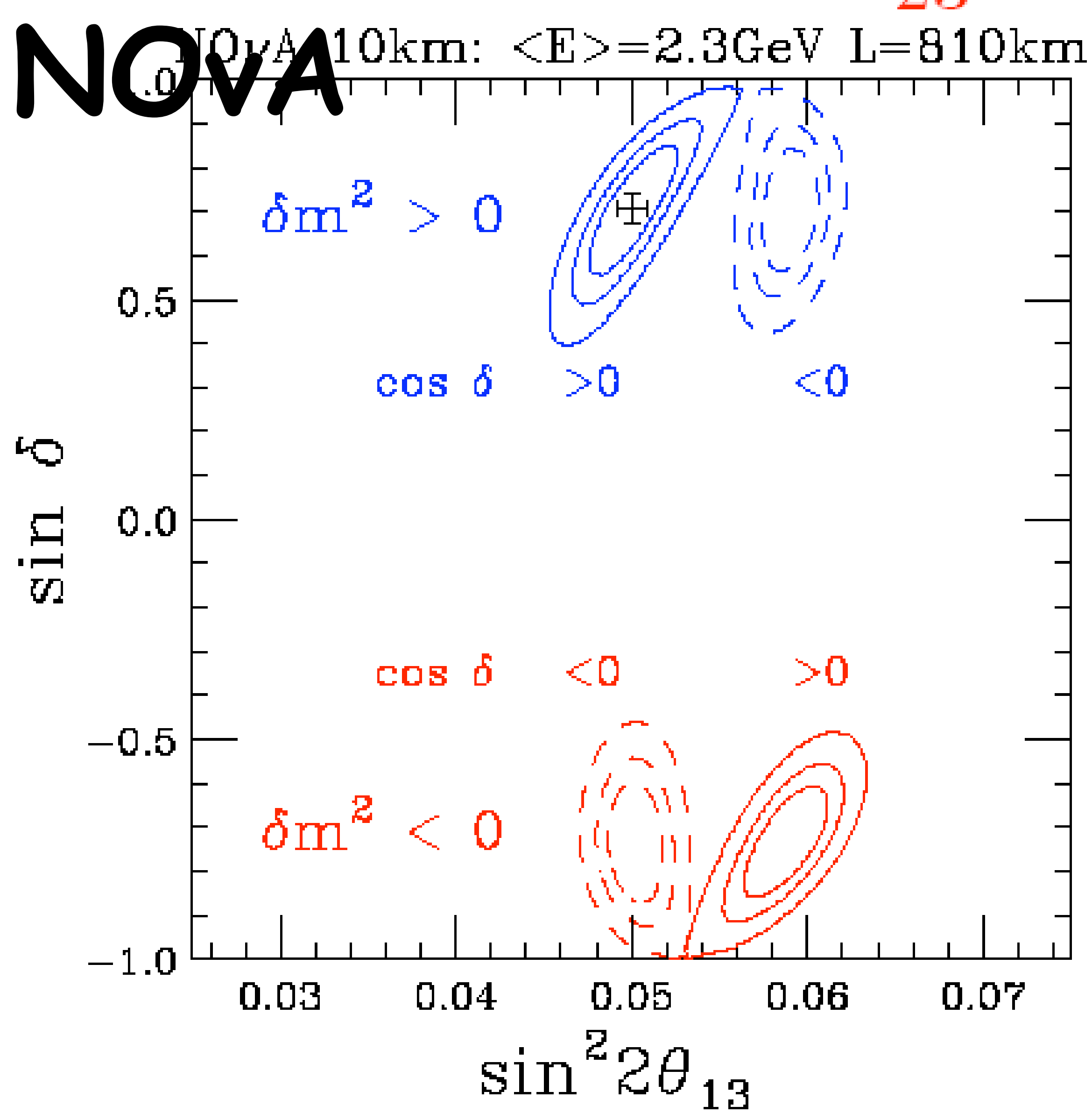


O.M and S.Parke, ``Untangling CP violation and the mass hierarchy in long baseline experiments,'' PRD70 (2004)

$\theta_{23} = \pi/4$



5 years in each polarity,0.75MW,HyperK



5 years in each polarity,4MW,50 kton

$$\langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- = 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}} \qquad \langle \sin\delta \rangle_+ - \langle \sin\delta \rangle_- = 1.41\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

$$|\langle \sin\delta \rangle^{T2K}_{fake} - \langle \sin\delta \rangle^{NO\nu A}_{fake}| = 0.94\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

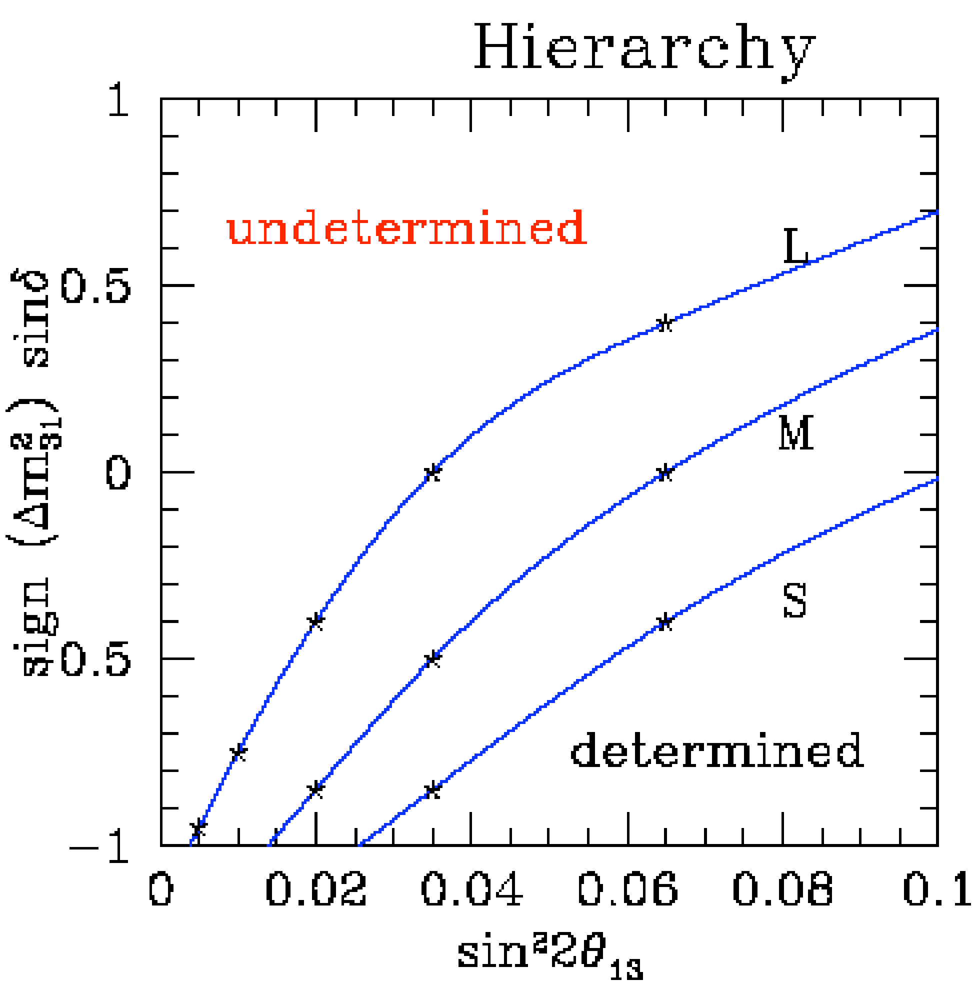
``Physics potential of the Fermilab NuMI beamline,''

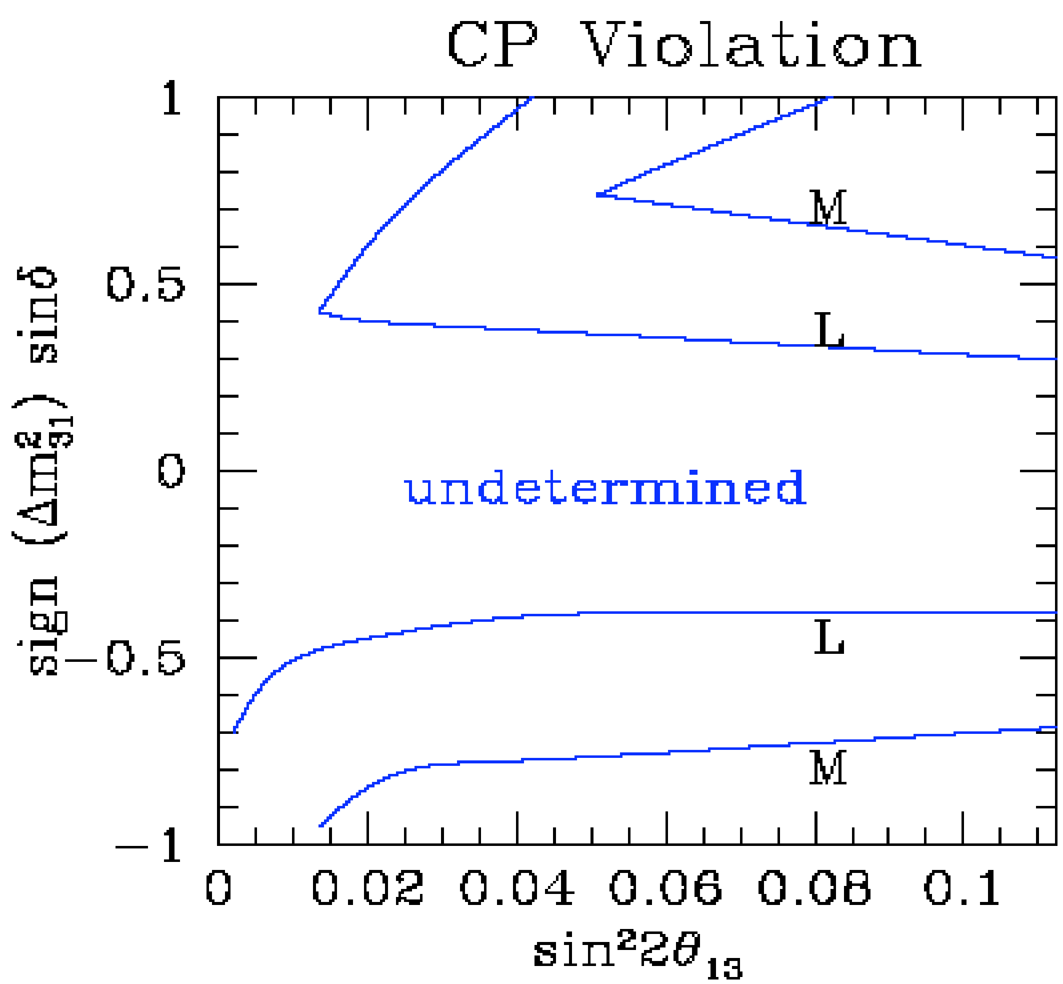
O.M and S. Parke, PRD (2005)

$$n_p \times m_D \times \epsilon = 3.3 \times 10^{22}$$ **(pot*kton)**

× 5 (M)

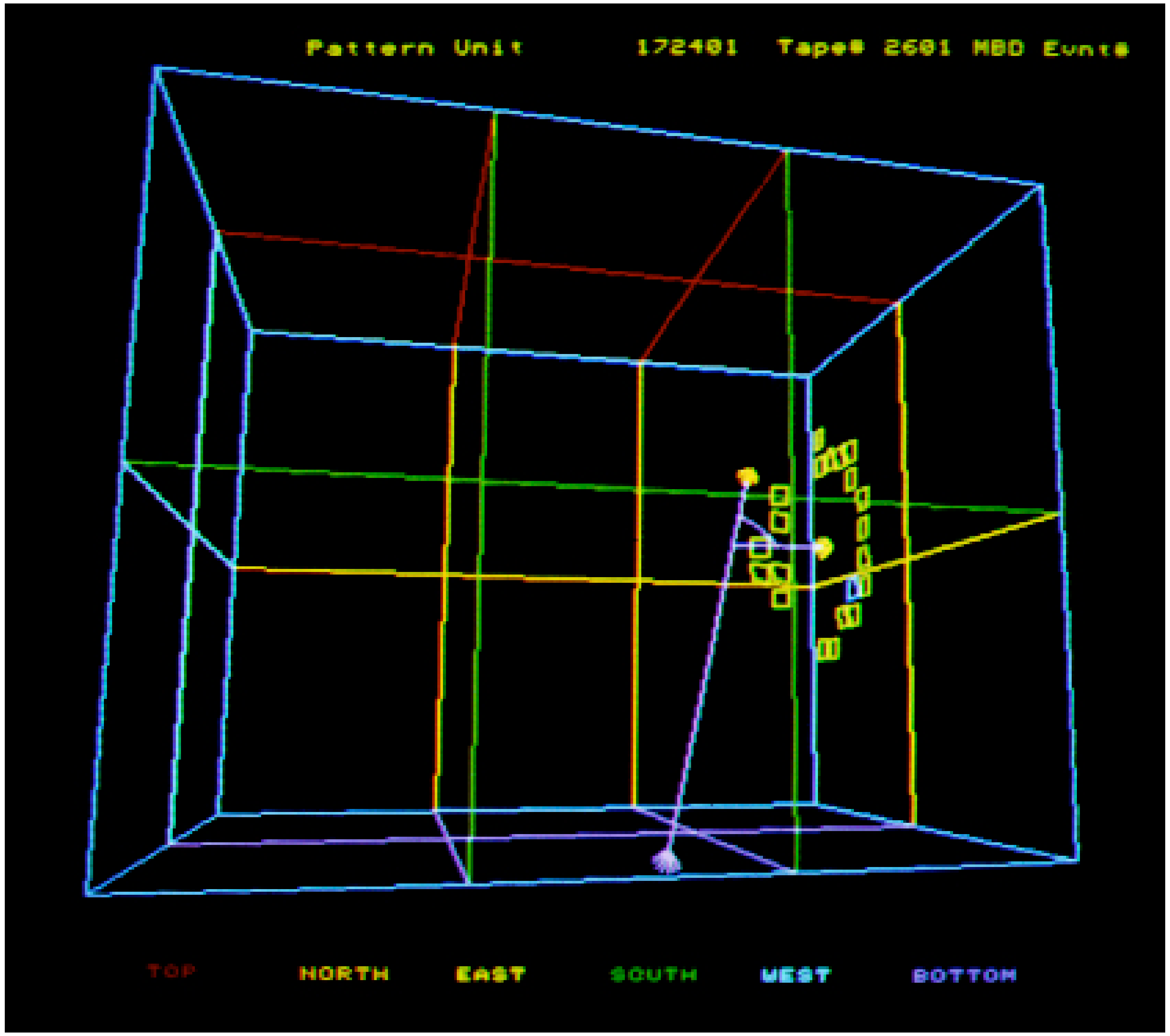
× 25 (L)





Supernova

neutrino event@IMB



SuperNOvA

``A long-baseline neutrino experiment with two off-axis detectors,''

O.M, S.Palomares-Ruiz and S.Pascoli, PRD (2005).

810km

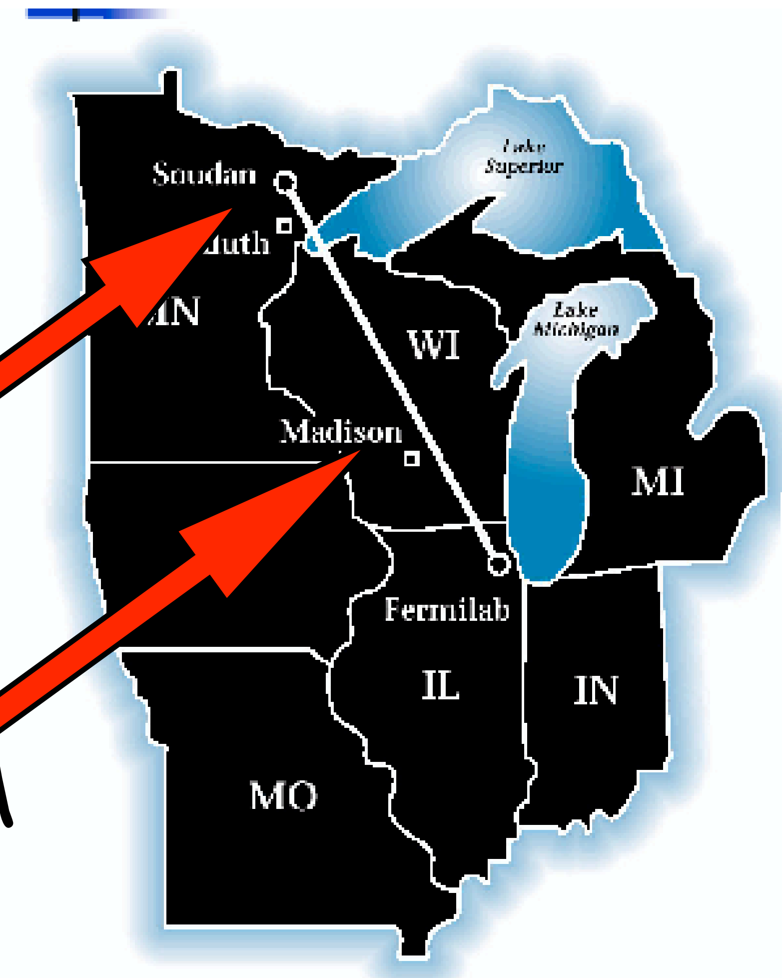
@ 10 km OA

2.3 GeV

200km

@ 8 km OA

0.7 GeV

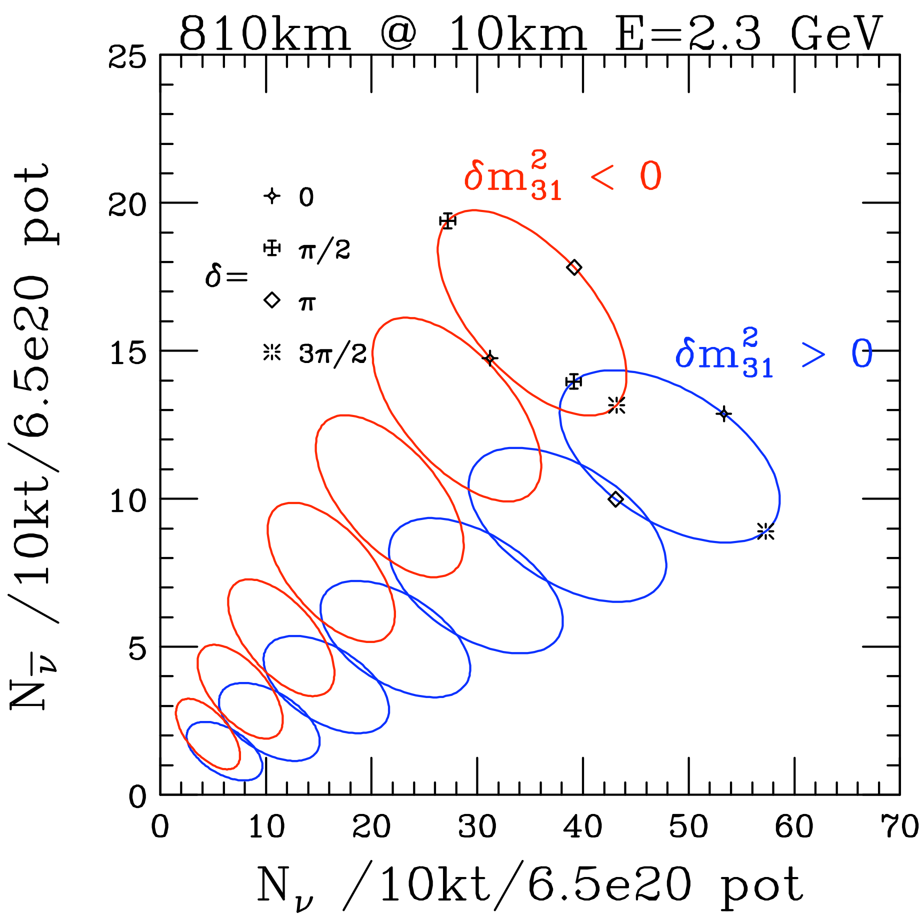


same E/L

H. Minakata, H. Nunokawa and S. Parke, PRD (2003).

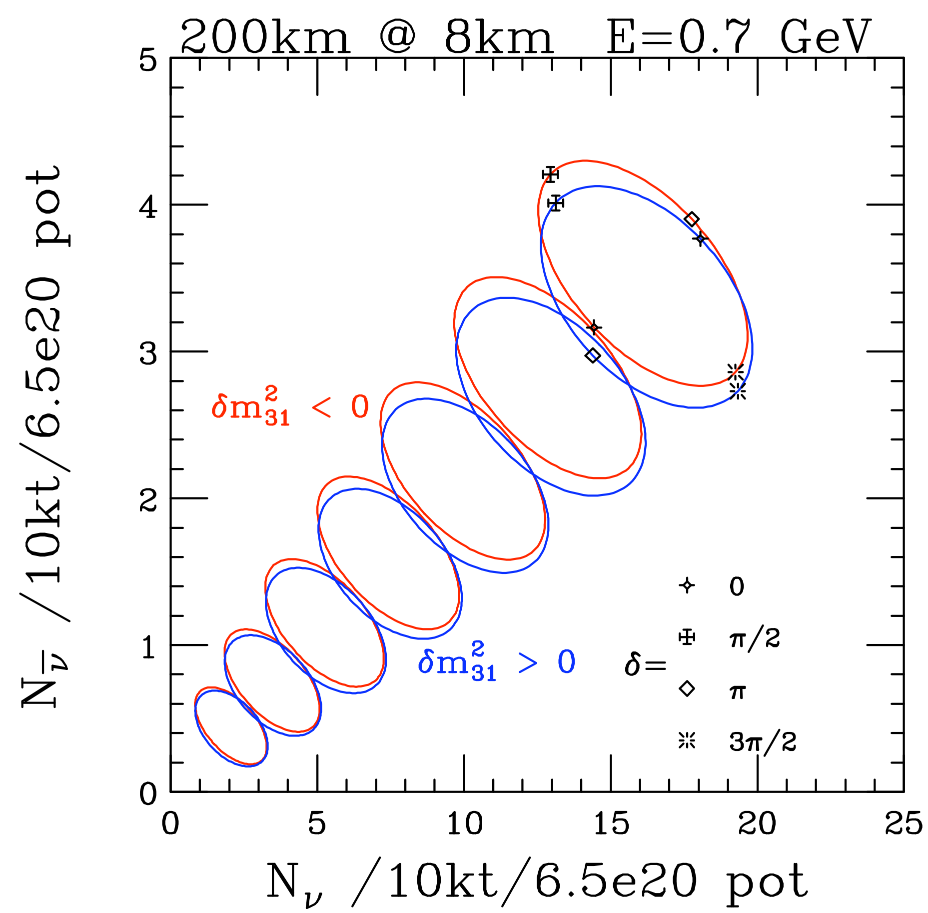
Neutrino - Antineutrino

NOvA



$\sin^2 2\theta_{13}$=(1, 2, 3, 4.3, 6, 7.4, 9.5) 10^{-2}

NEAR @ 200 km



$\sin^2 2\theta_{13}$=(1, 2, 3, 4.3, 6, 7.4, 9.5) 10^{-2}

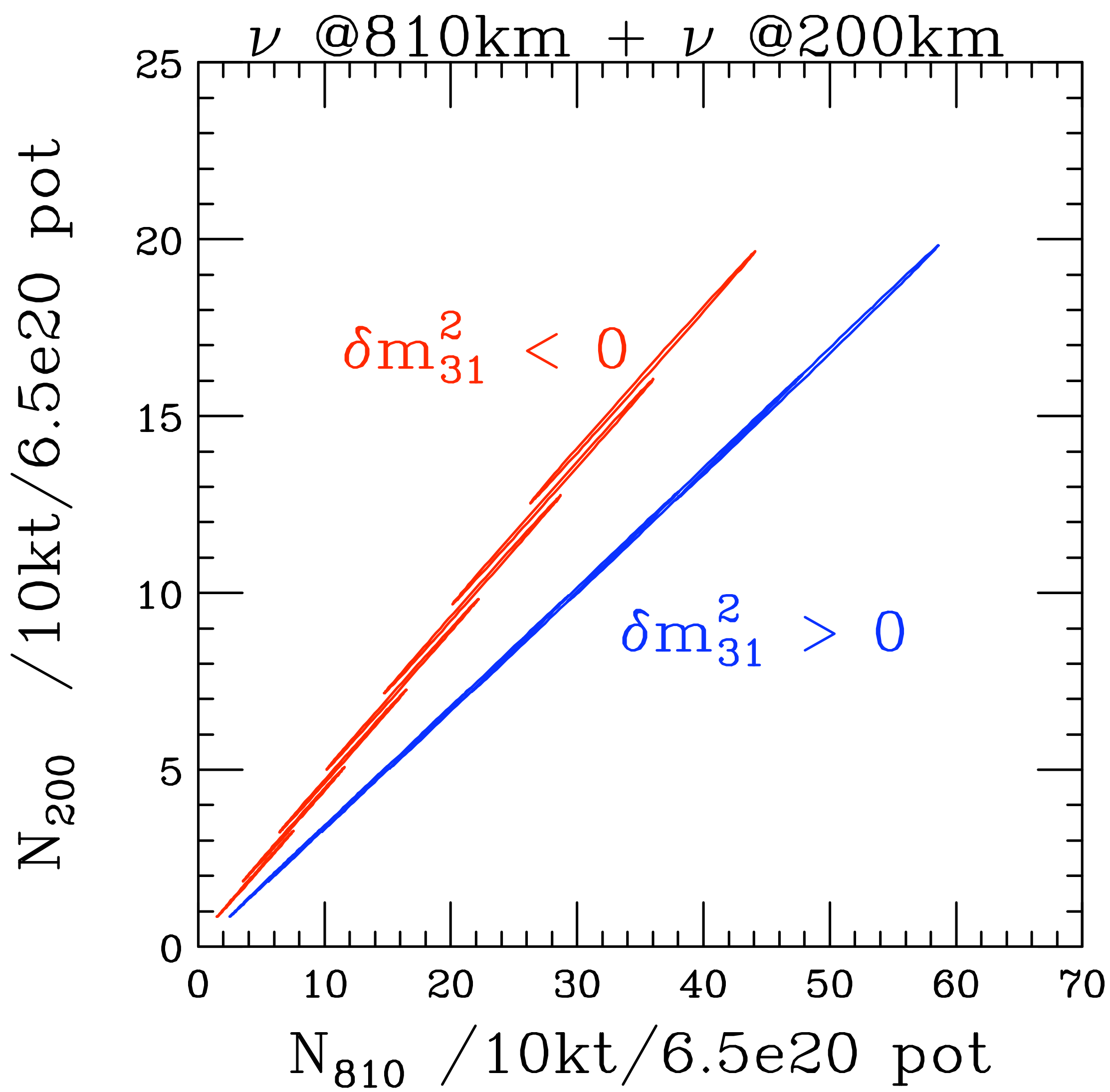
Neutrino - Neutrino

H. Minakata, H. Nunokawa and S. Parke, PRD (2003).

It is important that the matter effects are significantly different for both locations.

Ellipses flattens as the E/L's become identical.

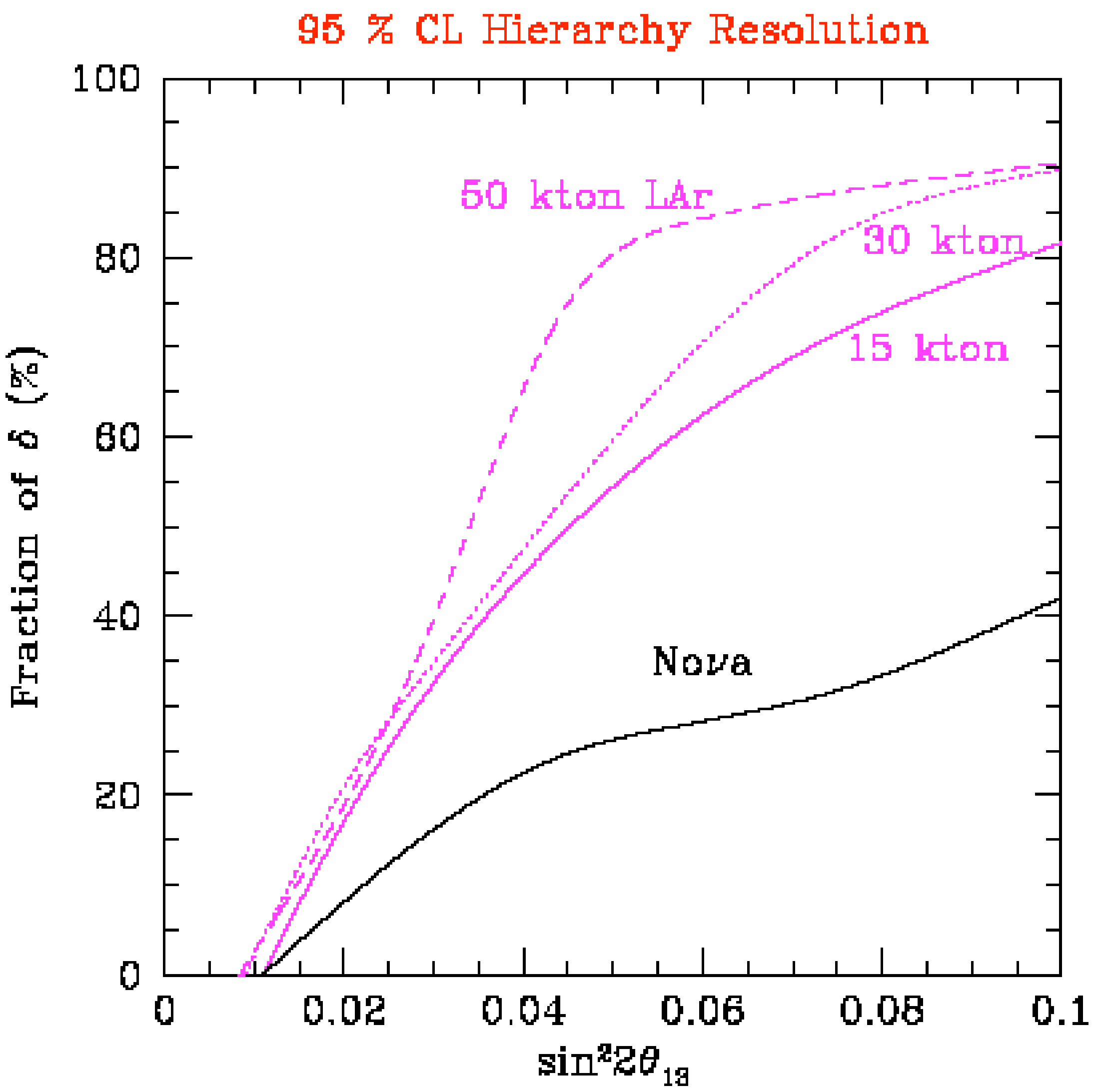
Even if the ratio of the slopes is large, the WIDTH is crucial, the ellipses might overlap: Keeping E/L constant KEY to resolve the hierarchy



$\sin^2 2\theta_{13}$=(1, 2, 3, 4.3, 6, 7.4, 9.5) 10^{-2}

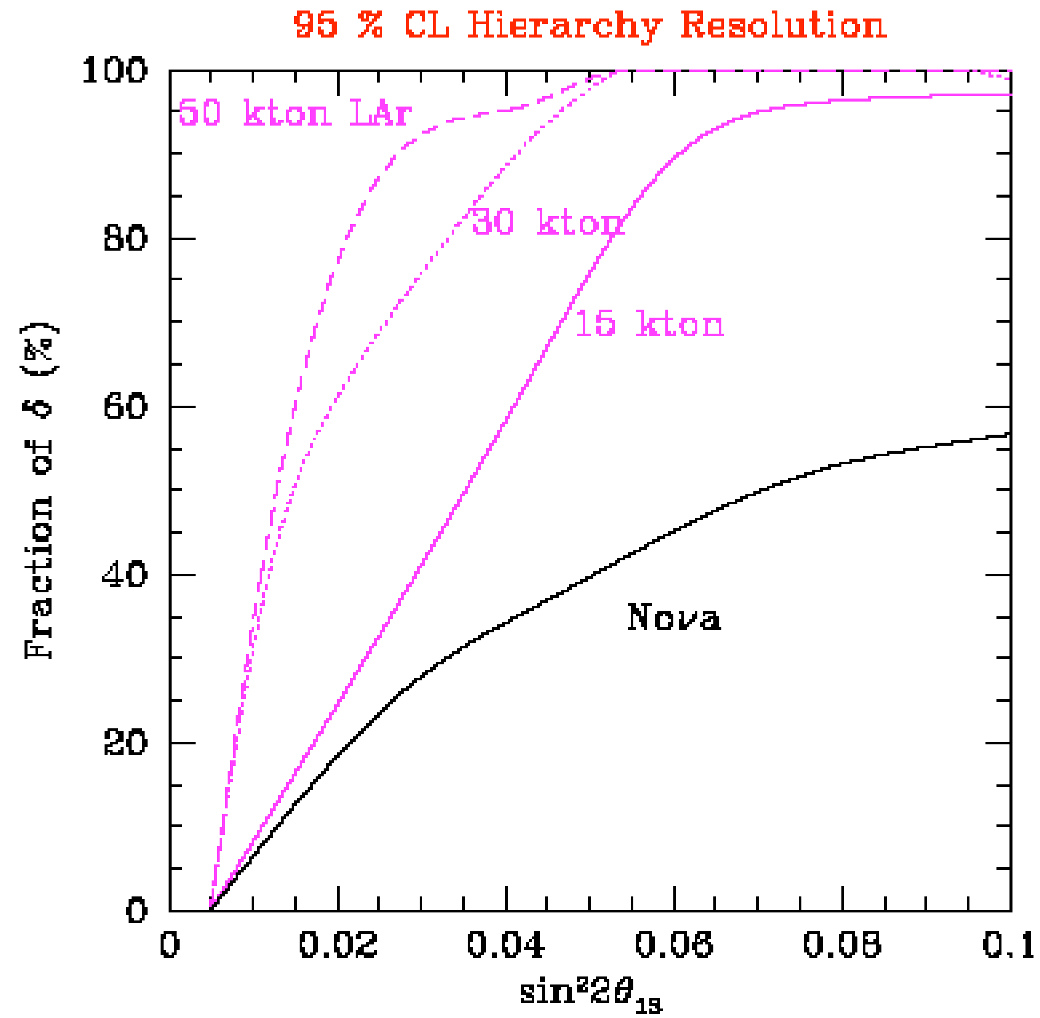
$$\frac{\alpha_+}{\alpha_-} \simeq 1 + 2\,(a_N L_N - a_F L_F)\left(\frac{1}{\Delta_{13}} - \frac{1}{\tan(\Delta_{13})}\right)$$

O.M, S.Palomares-Ruiz and S.Pascoli,``Determining the neutrino mass hierarchy and CP Violation in Nova with a second off-axis detector,'' hep-ph/0510182



Liquid Argon
Fid. Vols +
90% eff

NOvA
30 ktons
24% eff



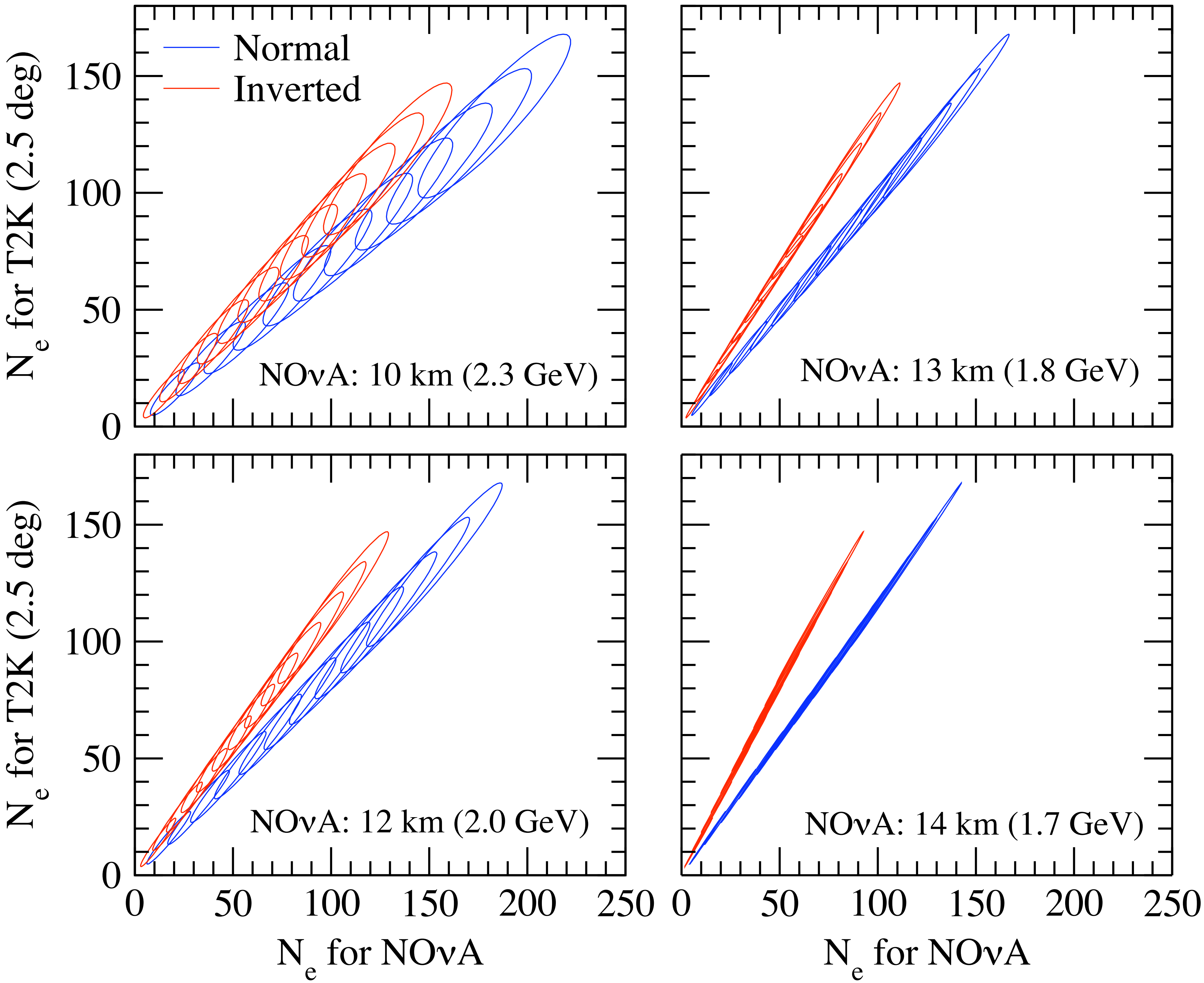
6.5 e20 pot/yr

Proton Driver: 25e20 pot/yr

Exposure (yrs):
Far: 3 nu + 3 nubar
Near + Far: 6 nu + 2 nubar

Exposure (yrs):
Far: 3 nu + 3 nubar
Near + Far: 3 nu + 1 nubar

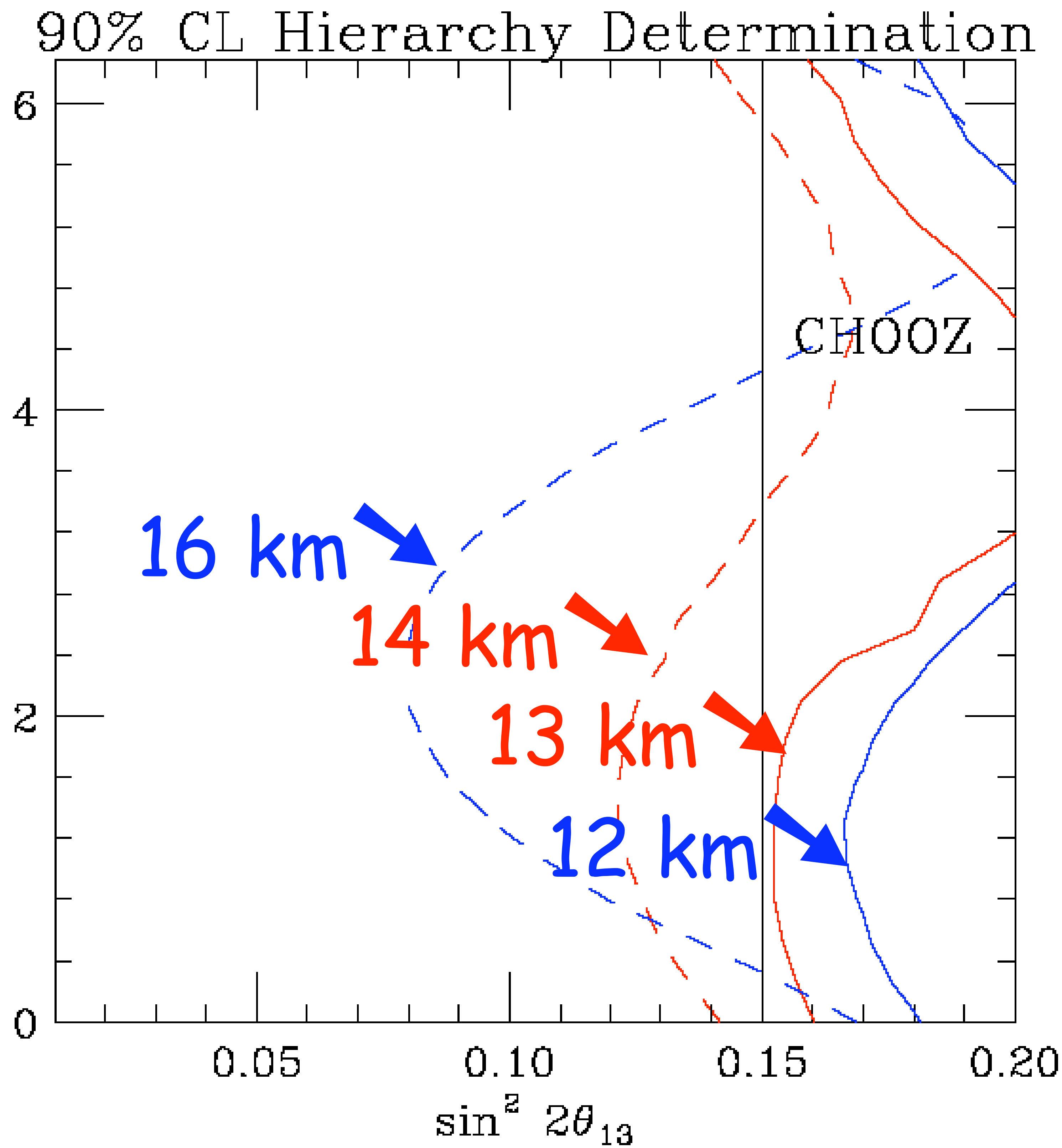
What about combining T2K and NOνA?



in coll. with H. Minakata, H. Nunokawa and S. Parke

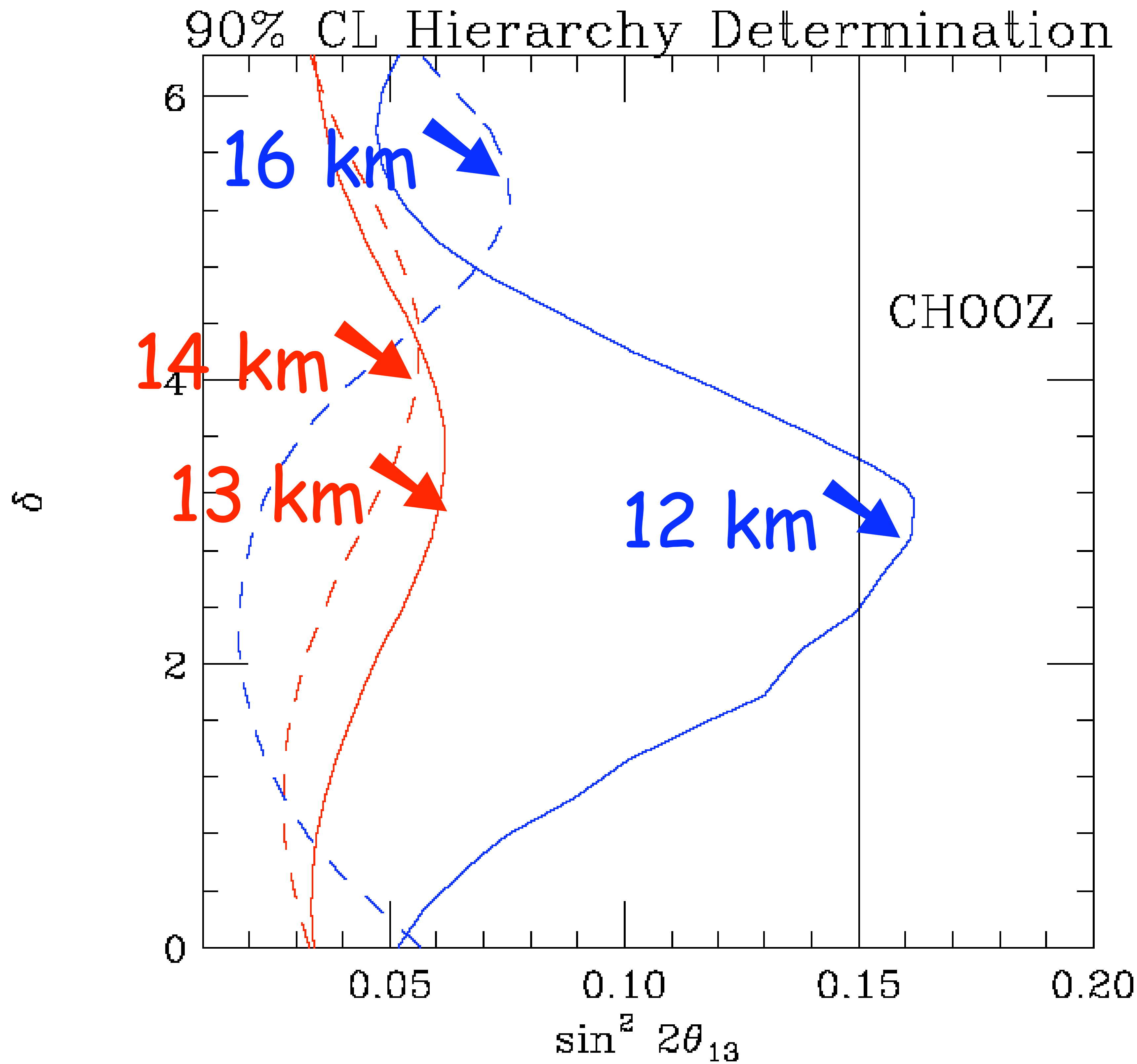
Phase I

Preliminary



Phase II (x 5)

Preliminary



Final remarks

We need to improve the precision of the known oscillation parameters and to measure the unknowns in the neutrino mass matrix.

Fermilab and Fermilab NuMI beamline could provide the ideal scenario for precision lepton flavor physics:

It is crucial to optimize the detector location if a second off-axis detector at a shortest distance (or at the second oscillation maximum, Bonnie Fleming's talk) is not available.

If a second detector is available, it could be possible to extract the mass hierarchy only with the neutrino channel.

Alternative techniques could also be developed (WBB, Beta Beams?)
With a Proton Driver the physics reach could be GREAT!